

## SECTION III. PRINCIPLES OF STEAM AND HOT WATER GENERATION

### 1-14. BASIC PRINCIPLES

The generation of steam occurs as a result of two separate processes: combustion, the release of heat by burning fuel, and heat transfer, the absorption of heat into the water. Combustion was discussed in the previous section. A study of the heat transfer process can be made with an elementary boiler as shown in figure 1-7. The boiler system can be represented as a container equipped with an outlet pipe and valve, a pressure gage, and a thermometer immersed in the water. If a fire is built under the unit and water at 32° F is put into the container with the valve left open, the water temperature will rise steadily as the fire burns until a temperature of approximately 212° F is reached. At this time, the temperature will rise no further, but the water will gradually boil off and, if firing is continued long enough, all the water will be evaporated. If the heat content of the fuel source is accurately measured, it can be demonstrated that to raise the temperature from 32° F to the boiling point, the heat input was 180 Btu for each pound of water. It would also be shown that 970 additional Btu for each pound of water is required to boil off all the water. This additional heat is called the latent heat of vaporization and represents the heat required to convert the small volume of liquid into a large volume of steam. With the valve in a closed position and using another batch of water, repeat the process and allow pressure to build up to 100 psig, then throttle the valve so that pressure is maintained at 100 psig. The temperature in the container will now be approximately 338° F. This is called the saturation temperature for 100 psig pressure. The heat input required to raise one pound of water from 32° F up to this saturation temperature is 309 Btu. The energy expended in boiling one pound of water from 338° F at 100 psig is 880.6 Btu. The temperature required to boil the water increases as the pressure increases. The amount of heat put into the liquid to raise it to this boiling point temperature is greater and the latent heat of vaporization is progressively less as the pressure increases. Table 1-9 provides a summary of saturation temperatures, energy in water, energy in steam, and latent heat of vaporization for pressures from zero to 300 psig.

### 1-15. HEAT TRANSFER

Heat transfer is accomplished by three methods: radiation, conduction, and convection. All three methods are used within a boiler. The heating surface in the furnace area receives heat primarily by radiation. The remaining heating surface in the boiler receives heat by convection from the hot flue gases. Heat received by the heating surface travels through the metal by conduction. Heat is then transferred

from the metal to the water by convection. Each of these methods is discussed in more detail below.

**a. Radiation.** Radiation is the most important method of heat transfer in the furnace. The amount of heat transfer depends on the area of the heating surfaces and hot surfaces in the furnace, the difference of the fourth powers of temperatures of the flame and heating surfaces, and the nature of the flame. For the same temperatures a coal flame is more radiant than an oil flame and an oil flame is more radiant than a natural gas flame. The same physical laws governing transmission of light also apply to the transfer of radiant heat:

- Heat is transmitted in straight lines
- Heat can be reflected and refracted
- Heat is radiated in all directions

Radiant heat can be transmitted through a vacuum, most gases, some liquids, and a few solids. The solid boiler tubes absorb the radiant heat from the flame and radiate a small portion of that heat back to the furnace.

**b. Conduction.** In conduction, heat is transferred through a material in which the individual particles stay in the same position. Heat flowing along an iron bar when one end of the bar is held in a fire is a simple example of this process. Conduction occurs when the material, called a conductor, is in physical contact with both the heat source and the point of delivery. Heat flows from the hot end to the cold end of the conductor. It makes no difference if the conductor is straight, crooked, inclined, horizontal, or vertical. The material of which it is made has a great effect, however. Metals conduct heat readily while liquids and gases conduct heat more slowly. Some materials conduct heat very poorly, and are called insulators. Common examples of insulators are asbestos, fiberglass, wood, and some types of plastics. The amount of heat transmitted also varies with the length of the path, the contact area, and the temperature difference.

**c. Convection.** Transfer of heat by convection can be compared to a bucket brigade in which each man carries the water from a supply point to a tank. In this example the medium is represented by the men and the heat is represented by the water. In convection, the gas or liquid medium receives heat from the source, expands, and is pushed away by colder, heavier particles of the medium. The fluid which receives heat then transfers the heat to a new location, losing some heat in the process. It may or may not return to its source to repeat the cycle. Heat transfer by convection normally occurs from a lower to a higher elevation. However, transfer in any direction may take place if an external force, such as fans, pumps, or a pressure drop, is applied.

**d. Gas Flow Considerations.** In most boilers, a large

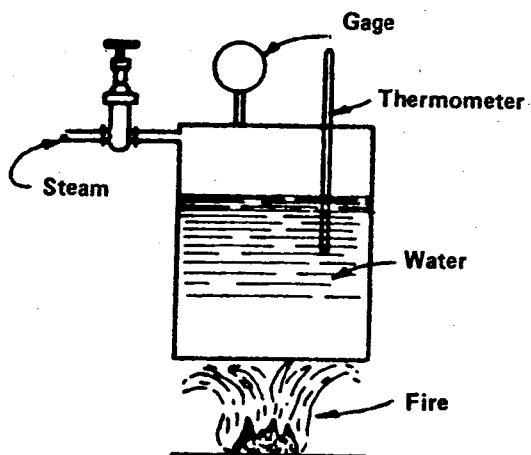


FIGURE 1-7. ELEMENTARY BOILER

Table 1-9. Water/Steam Characteristics

Pressure (psig)	Saturation Temp (°F)	Energy in Water (Btu/lb)	Energy in Steam (Btu/lb)	Latent Heat of Vaporization (Btu/lb)
0	32*	0	-	-
0	60*	28	-	-
0	212	180	1150	970
15	250	218	1164	946
30	274	243	1172	929
40	287	256	1176	920
50	298	267	1179	912
60	307	277	1182	905
70	316	286	1184	898
80	324	294	1186	892
90	331	302	1188	886
100	338	309	1190	881
110	344	316	1191	875
120	350	322	1192	870
130	356	328	1193	865
140	361	333	1195	862
150	366	339	1196	857
200	388	362	1199	837
250	406	382	1202	820
300	422	399	1203	804

\* 32°F and 60°F are not saturation temperatures of water at 0 psig.

part of the absorbed heat is given up by hot flue gases which sweep over the heat-absorbing surfaces. Heat transfer takes place by convection. The quantity of heat transferred can be varied by controlling the temperature or quantity of the flue gases. Usually both are controlled. The ability of materials to resist the damaging effects of high temperatures is the limiting factor in the first case, and the force available for causing flow through the boiler is the limiting factor in the second. Boiler draft loss or resistance to flow is the force or pressure drop required for gases to flow through a boiler. Draft loss is commonly called "draft" and may be supplied by a chimney, forced draft fan, or induced draft fan. Draft, which is measured in inches of water, depends primarily on velocity and density of the flowing gases, and cross-sectional area and length of the gas passage. Draft loss increases with the square of the velocity and directly with the length of the passage. Thus, force required to maintain the proper flow increases by a factor of four when velocity is doubled, and by a factor of two when the passage length is doubled. It is important to keep velocity at a minimum, consistent with the requirements of good convective heat transfer, if the maximum output of a boiler installation is to be attained. The cross-sectional area, baffle arrangement, and length of the gas passage are usually fixed. If gas passages are kept free of soot and ash accumulation, gas velocity and draft loss will depend solely on the quantity of gas flow which in turn depends on the quantity of air supplied to burn the fuel. A minimum air supply consistent with good combustion practice therefore minimizes draft loss and helps to maximize heat transfer and boiler output.

**e. Water Circulation Considerations.** Water circulates in a steam boiler because the density of water is greater than the density of the water/steam mixture. Reference figure 1-8. Within the boiler the more dense water falls while the less dense mixture rises. Table 1-10 illustrates the relationships of water and steam mixtures at 15 psig, 100 psig, and 400 psig. As noted in table 1-10, the volume ratios become smaller as pressures increase. Natural circulating forces are thus reduced as the operating pressure of a boiler increases, and increased as the percent of steam in the mixture increases. Hot water boilers normally use pumps to force the circulation of water through the boiler, because the density difference between cold and hot water is not large enough to cause natural circulation with the velocities necessary for good heat transfer.

**f. Heat Transfer to Boiler Tubes and Water by Convection.** Heat transfer by convection depends on the temperature and velocity of the gases on one side of the boiler tube and the velocity of the water on the other side. Heat can be transferred to quiet water at the rate of approximately 2.8 Btu per hour per square foot per degree Fahrenheit of temperature difference (2.8 Btu/hr/ft<sup>2</sup>/°F).

Increasing the velocity of the water aids convection and increases heat transfer to about 1,500 Btu/hr/ft<sup>2</sup>/°F. This is due to a very thin film of stagnant water which is in contact with the boiler tube. This can be demonstrated by a simple experiment using a Bunsen burner and a metallic vessel containing boiling water as shown in figure 1-8. Place the lighted burner under the vessel and observe it closely. Note that the flame spreads into a sheet about 1/30 to 1/40 inch from the vessel. Because of its high conductivity, the temperature of the tube is only a few degrees hotter than the water while the temperature of the burner flame is much higher. Therefore, there must be a large temperature drop through the thin film between the flame and the vessel. This principle applies to both the water and gas sides of the vessel. The heat in the boiler tube must be conducted through the thin stagnant film of water before the active convection process begins. Heat transfer can be greatly increased if this film is reduced in thickness, or eliminated completely. Usually, this is accomplished by increasing the flow velocity across the surface and scrubbing the film away. Unfortunately, as was mentioned earlier, increasing velocities increases draft losses and power requirements. The thin film does not affect radiant or conductive heat but only convective heat.

**g. Optimizing Heat Transfer.** Boiler furnace heat is absorbed by a combination of radiation and convection. The absorbed heat is conducted through the boiler tubes. Water in the boiler tubes is heated by convection. Tubes and other heating surfaces close to the fire which do not have a high rate of gas flowing across them receive practically all their heat by radiation. Heating surfaces close to the furnace and across which the gas flow is high receive heat by both radiation and convection. Surfaces distant from the furnace receive all their heat by convection. Heat transfer can be optimized by controlling excess air, keeping boiler tubes clean, and maintaining optimum gas and water velocities.

**(1) Excess Air Control.** The rate at which radiant heat is transmitted varies as the fourth power of the absolute or Rankine temperature. (Rankine temperature is based on a scale whose zero represents a complete absence of heat; 0° R is approximately minus 460° F. To convert from Fahrenheit to Rankine, add 460° to Fahrenheit temperature.) The amount of heat transmitted by radiation doubles when the absolute temperature of the radiating source is increased by approximately 19 percent. The rate at which heat is transmitted by radiation from a fuel bed at a temperature of 1050° F (1510° R) can be doubled by increasing the temperature of the refractory wall or bed to 1350° F (1810° R). The rate at which heat is transmitted by radiation from an oil flame can increase by 42 percent by increasing the temperature of the visible flame from 1725° F to 1925° F (2185° R to 2385° R).

Table 1-10. Water/Steam Mixtures

Mixture		Specific Volume, (ft <sup>3</sup> /lb)			Volume Ratio = $\frac{\text{volume of mixture}}{\text{volume of water}}$		
%		Pressure(psig)			Pressure(psig)		
Steam	Water	15	100	400	15	100	400
0.0	100.0	.0170	.0179	.0194	1.00	1.00	1.00
0.1	99.9	.0309	.0217	.0205	1.82	1.21	1.06
0.2	99.8	.0448	.0256	.0216	2.64	1.43	1.11
0.5	99.5	.0863	.0370	.0249	5.08	2.08	1.29
1.0	99.0	.1556	.0562	.0305	9.15	3.15	1.57
100.0	0	13.88	3.88	1.12	816	217	57.8

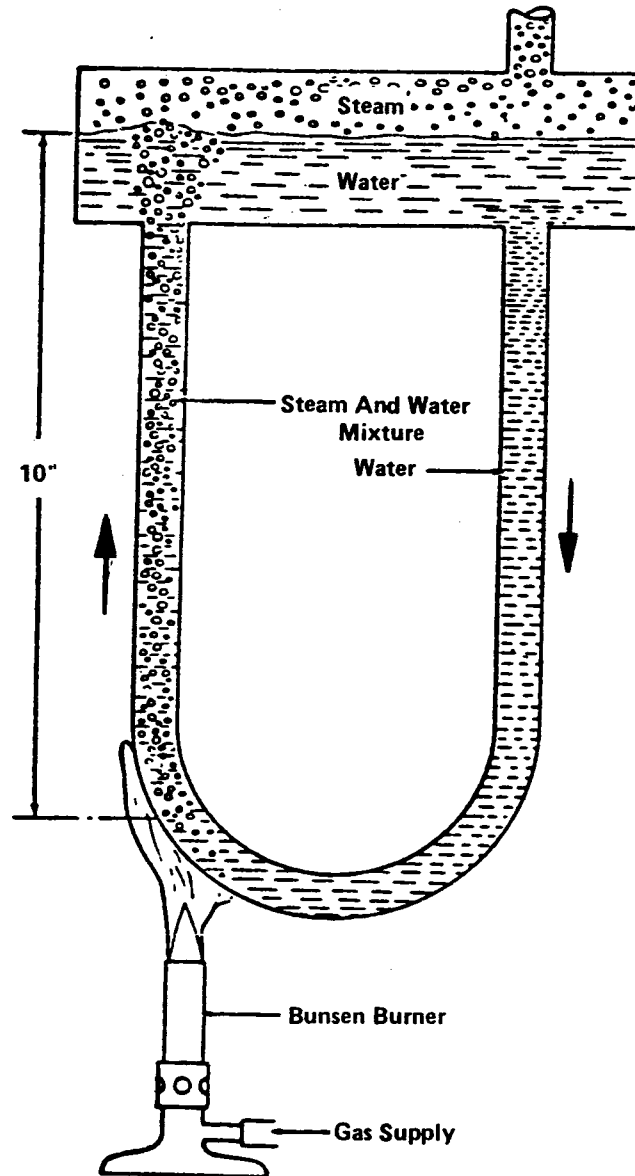


FIGURE 1-8. WATER CIRCULATION

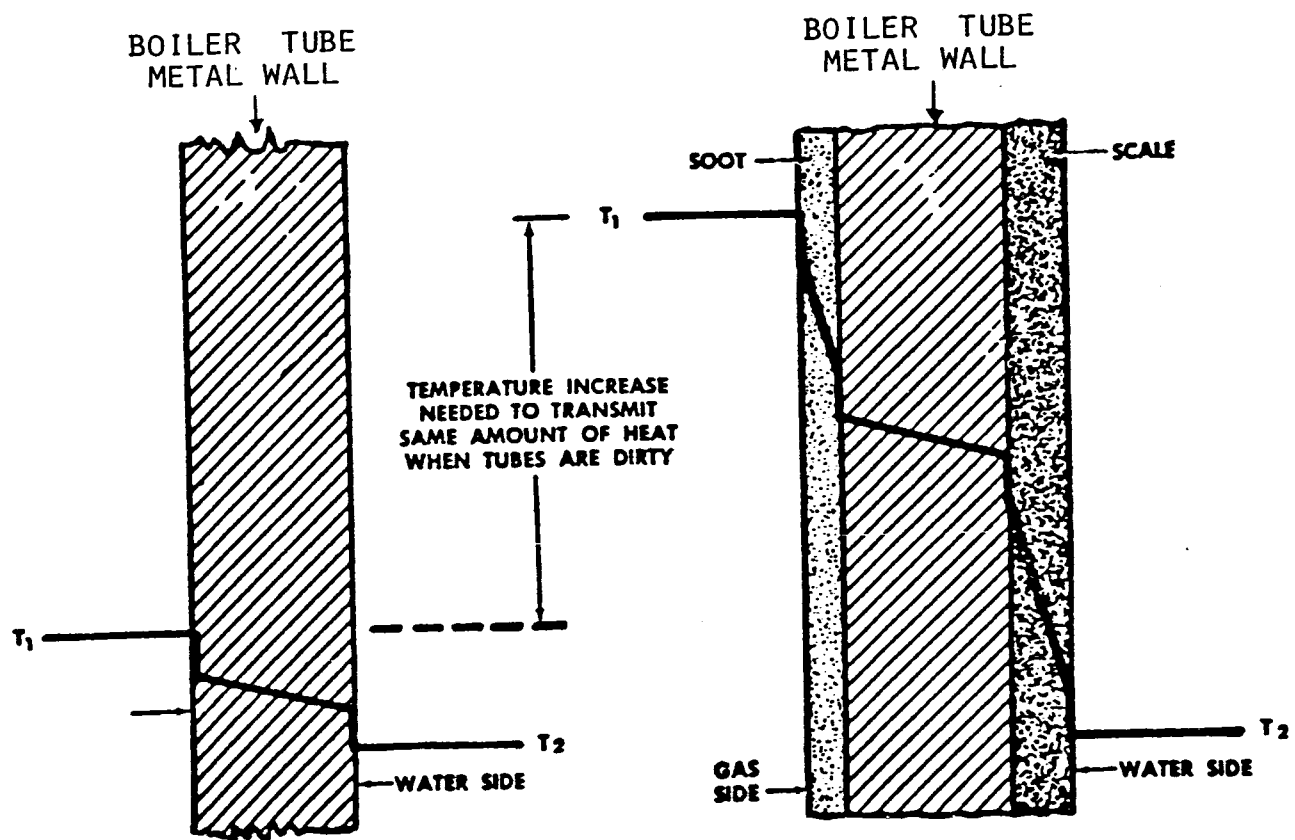


FIGURE 1-9. EFFECT OF SOOT AND SCALE ON HEAT TRANSFER

Reducing the excess air used to combust fuel causes the flame temperature to increase. Maximum flame temperature is normally obtained with approximately 3 to 5 percent excess air. A moderate increase in furnace temperature resulting from an excess air reduction can markedly affect the amount of radiant heat absorbed by the boiler surfaces.

(2) **Maintaining Clean Boiler Tubes.** The amount of heat transferred by conduction depends on the type, thickness, and condition of the conductive material as well as the difference in temperature. Heat is readily conducted through metal, while ash, soot, and scale are poor conductors. Figure 1-9 illustrates the effects of soot and scale. If the heating surfaces become coated with soot, scale, or other material the firing rate of the boiler must be increased to raise gas temperatures and maintain the same amount of heat transfer. Any deposit on either side of the heating surface increases maintenance costs, reduces efficiency, and may cause operator injuries or boiler damage if a tube overheats and ruptures. Reference paragraphs 3-16d and 3-34 for further information.

(3) **Maintaining Gas and Water Passages.** Keeping gas passages free from accumulations of soot and ash and maintaining gas baffles in good repair help to ensure proper gas velocities to all heat transfer surfaces. Keeping water passages free from accumulations of sludge and scale ensures proper water flow and velocity for cooling of the

heat transfer surfaces and generating steam or hot wa

(4) **Maximum Versus Economical Heat Transfer.** Maximum and economical heat transfer are not the same. It is rarely possible to operate a boiler at temperatures high enough to obtain the maximum heat transfer rate because of material limitations, particularly of furnace brickwork. The maximum temperature which can be safely maintained is determined by, among other considerations, the kind of firebrick used, furnace construction (self-supporting, or supported), the quantity and kind of ash in the fuel, furnace size, and the amount and type of cooling of the furnace walls (air cooled or water cooled). It is important to maintain a low gas temperature at the boiler outlet since this results in high boiler efficiency. However, the rate of heat transfer may be relatively low in this area because temperature differences are low. There is a practical limit on the velocity of flue gas based on reasonable fan horsepower requirements and capabilities as discussed in paragraph 1-15d. Water velocity is fixed by boiler design and cleanliness for any particular firing rate. Reduced water velocity at a lower boiler firing rate results in reduced but more economical heat transfer rates. Most of the above factors are determined by the design of the boiler. It is the responsibility of the boiler manufacturer to balance the requirements of maximum heat transfer with economy and produce a cost-effective design.